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This DoD HPC Challenge project is part of a coordinated 6.1-6.4 effort on the "Grand Challenge" problem of eddy-resolving global and basin-scale ocean modeling and prediction. This project is work towards the ultimate goal of a data assimilative 1/32° global ocean nowcast/forecast system including the associated basic research and exploratory development. The interim goal by 2001 is the transition of a 1/8° global system with embedded 1/16° Pacific north of 20°S and 1/32° subtropical Atlantic (9-51°N) including the Caribbean and Gulf of Mexico. A data assimilative 1/4° global system was transitioned to Fleet Numerical Meteorology and Oceanography Center (FNMOC) for operational evaluation early in FY98 and the 1/16° Pacific system is scheduled for transition by the end of FY99. A two pronged approach is used in this DoD Challenge effort. The first is ocean nowcast experiments with data assimilation and ocean forecasting experiments initialized from the experiments with data assimilation, 1/16° Pacific in FY98-99 and 1/32° subtropical Atlantic in FY00. The second prong is "first of a kind" ocean model simulations at the next higher resolution, 1/16° global (completed under an FY97 DoD HPC Challenge project), 1/32° Pacific north of 20°S and 1/64° subtropical Atlantic in FY98-99 (currently underway in an FY98-00 DoD HPC Challenge project) and 1/32° global in FY00, the ultimate target resolution for a global nowcast/forecast system. These simulations provide information on the value added of increased resolution and input on tradeoffs between increased resolution and model modifications which make it more expensive to run. Research topics include ocean dynamics, model development and portability to different computer architectures, ocean simulation, model validation, data assimilation, ocean nowcasting and forecasting, observing system simulation, and applications of naval interest.

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Global and Basin-Scale Ocean Modeling and Prediction

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Abstract

This DoD HPC Challenge project is part of a coordinated 6.1-6.4 effort on the "Grand Challenge" problem of eddy-resolving global and basin-scale ocean modeling and prediction. This project is work towards the ultimate goal of a data assimilative 1/32° global ocean nowcast/forecast system including the associated basic research and exploratory development. The interim goal by 2001 is the transition of a 1/8° global system with embedded 1/16° Pacific north of 20°S and 1/32° subtropical Atlantic (9-51°N) including the Caribbean and Gulf of Mexico. A data assimilative 1/4° global system was transitioned to Fleet Numerical Meteorology and Oceanography Center (FNMOC) for operational evaluation early in FY98 and the 1/16° Pacific system is scheduled for transition by the end of FY99. A two pronged approach is used in this DoD Challenge effort. The first is ocean nowcast experiments with data assimilation and ocean forecasting experiments initialized from the experiments with data assimilation, 1/16° Pacific in FY98-99 and 1/32° subtropical Atlantic in FY00. The second prong is "first of a kind" ocean model simulations at the next higher resolution, 1/16° global (completed under an FY97 DoD HPC Challenge project), 1/32° Pacific north of 20°S and 1/64° subtropical Atlantic in FY98-99 (currently underway in an FY98-00 DoD HPC Challenge project) and 1/32° global in FY00, the ultimate target resolution for a global nowcast/forecast system. These simulations provide information on the value added of increased resolution and input on tradeoffs between increased resolution and model modifications which make it more expensive to run. Research topics include ocean dynamics, model development and portability to different computer architectures, ocean simulation, model validation, data assimilation, ocean nowcasting and forecasting, observing system simulation, and applications of naval interest.

Objectives

This DoD Challenge project is part of a coordinated 6.1-6.4 effort on the "Grand Challenge" problem of eddy-resolving global and basin-scale ocean modeling and prediction. The long term objectives are to simulate, understand, nowcast and forecast the global ocean circulation, and to increase the capability to model it. Research topics include ocean dynamics, model development and portability to different computer architectures, ocean simulation, model validation, data assimilation, ocean nowcasting and forecasting, observing system simulation, and applications of naval interest. In addition, the ocean model and model output are made available to researchers outside NRL. This DoD HPC Challenge effort directly supports 5 funded projects: 6.1 Thermodynamic and Topographic Forcing in Global Ocean Models (ONR), 6.1 Dynamics of Low Latitude Western Boundary Currents (ONR), 6.2 Basin Scale Prediction Systems (ONR), 6.3 Scalable Ocean Models with Domain Decomposition and Parallel

Model Components (CHSSI), and 6.4 Large Scale Ocean Prediction (SPAWAR). Applications for the models and the nowcast/forecast systems include assimilation and synthesis of global satellite surface data; ocean prediction; optimum track ship routing; search and rescue; anti-submarine warfare and surveillance; tactical planning; high resolution boundary conditions that are essential for even higher resolution coastal models; inputs to ice, atmospheric and bio-physical models and shipboard environmental products; environmental simulation and synthetic environments; observing system simulations; ocean research; pollution and tracer tracking and inputs to water quality assessment. Assimilation of satellite altimeter data into the models will make more effective use of near realtime altimeter data from the Navy's Geosat Follow On (GFO) mission, TOPEX/POSEIDON and ERS-2 via NAVOCEANO's Altimeter Data Fusion Center (ADFC). Other data will be assimilated as well.

Approach and Planned Research

Overall, this effort is work towards the goal of developing a data assimilative 1/32° global ocean nowcast/forecast system for transition to Fleet Numerical Meteorology and Oceanography Center (FNMOC). This includes plans to participate in a multi-national Global Ocean Data Assimilation Experiment (GODAE) planned for 2003-2005, in addition to preceding pilot programs. Our effort is already represented on the Scientific Steering Team for GODAE. The interim goal by 2001 is the transition of a 1/8° global system with embedded 1/16° Pacific north of 20°S and 1/32° subtropical Atlantic (9-51°N) including the Caribbean and Gulf of Mexico. A data assimilative 1/4° global system was transitioned to FNMOC for operational evaluation early in FY98 and has given a very clear picture showing the evolution of the 1997-98 El Niño (Metzger, et al., 1998). The 1/16° Pacific system is scheduled for transition by the end of FY99.

The Pacific component and all subsequent systems of this type are being designed for deployment on a scalable computer. Since FNMOC does not yet have such a machine, they will initially be deployed on the T3E at NAVO and later migrated to a scalable computer system at FNMOC when available. These systems will serve as the backbone of a globally relocatable ocean nowcast/forecast capability that will address the Naval need for littoral or deep water support anywhere in the world.

A two pronged approach is used in this DoD HPC Challenge effort. The first is ocean nowcast experiments with data assimilation and ocean forecasting experiments initialized from the experiments with data assimilation. The second is "first of a kind" ocean model simulations at the next higher resolution, 1/32° Pacific north of 20°S, 1/64° subtropical Atlantic (FY98-99) and 1/32° global (FY00). 1/16° global ocean simulations were completed under an FY97 DoD HPC Challenge Project on the CEWES T3E. The "first of a kind" simulations in the Atlantic and Pacific are presently being run under an FY98-00 DoD HPC Challenge Project on the T3E-900 at NAVO. However, these simulations could be run efficiently and interchangeably on any computer system configured to handle simulations this large (if it has a single global scratch file system) because the NRL Layered Ocean Model (NLOM), used for the simulations, is scalable and portable using a tiled data parallel programming paradigm (Wallcraft and Moore, 1997). This approach is general enough that the technique used to obtain scalability on a given computer system can be selected at compile time from (1) data parallel, (2) SPMD message passing, (3) autotasking or (4) SPMD message passing between multi-processor autotasked systems.

The simulations within this project (except for 1/32° global) can run in existing large queues on several

supercomputers within DoD HPC, but turnaround for large jobs is historically poor. Through DoD HPC Challenge resources we can obtain sufficient turnaround to accomplish the stated R&D goals.

The first of a kind ocean model simulations demonstrate the leading edge capability to model the ocean and typically are possible about 5 years before such simulations can be done routinely. In addition to demonstrating future potential for ocean models, they are critical in decision making when formulating future plans. For example, they provide information on value added of increased resolution and input on tradeoffs between increased grid resolution and model modifications which make it more expensive to run. NLOM has a factor of 10s to 100s advantage in computer time requirements over other global and basin-scale ocean models. In conjunction with a set of simulations performed at coarser resolution, these simulations contribute vital input in answering scientific questions about oceanic dynamics.

Resolution Requirements for Ocean Modeling

A critical issue in forecast system design is determining the resolution required. Ocean models require finer resolution and more computer time than atmospheric models in part because the space scales for variability due to flow instabilities (oceanic mesoscale eddies vs. atmospheric high and lows) are about 20-30 times smaller than found in the atmosphere. We need to resolve the oceanic eddy space scale very well because (1) it is relevant for most of the Navy applications listed earlier, (2) these models need to provide high resolution boundary conditions for even higher resolution coastal models, (3) upper ocean - topographic coupling via flow instabilities has a major impact on the pathways of many upper ocean currents (including mean pathways) and very fine resolution of the flow instabilities is required to get sufficient coupling (Hurlburt, et al., 1996; Hogan and Hurlburt, 1997; Hurlburt and Metzger, 1998), (4) very fine resolution is required to obtain (a) inertial jets and sharp oceanic fronts which span major ocean basins as observed (Hurlburt, et al., 1996) and (b) the associated nonlinear recirculation gyres which affect the shape of large-scale ocean gyres (Hurlburt and Hogan, 1998), (5) it is necessary to resolve small islands and narrow passages which affect current pathways and current transports in many regions, (6) in data assimilative mode we do not want the ocean model to "fight" the data because the natural behavior of the ocean model is inconsistent with the observations, and (7) a very high horizontal resolution model is needed to help get an accurate mean sea surface height field to add to the deviations obtained from satellite altimetry (observations alone do not provide sufficient resolution to do this).

How much resolution is required to accomplish these goals? Do we see evidence of solution convergence as the resolution is increased? Sea of Japan simulations (Hogan and Hurlburt, 1997) show major impact from increasing the resolution up to 1/32°, but relatively modest changes with a further increase to 1/64°. However, a Sea of Japan model cannot be used to address issues like (4) and (5) above. These are addressed by the 1/64° Atlantic simulation running as part of this DoD Challenge project, a region where again we have already seen major impact from resolution increases up to 1/32° (Hurlburt and Hogan, 1998).

Results from FY97 and FY98-00 DoD HPC Challenge Projects to date

A 1/16° global ocean model was run on the CEWES T3E under an FY97 DoD HPC Challenge project. Before extension at 1/16° resolution, it was spun up from rest to statistical equilibrium at progressively

higher resolutions (1/2°, 1/4° and 1/8°) outside DoD Challenge forced by monthly climatological winds. It was continued to near equilibrium at 1/16° resolution with the climatological forcing. Then two "identical twin" simulations, initialized at two different times from the climatological simulation, were run 1979-1996 forced by 6 hourly reanalysis winds (1979-93) and archived operational winds (1994-96) from the European Centre for Medium-range Weather Forecasts (ECMWF). The first simulation was run under the DoD Challenge project, the second under early access on the NAVO T3E. The simulations showed many of the benefits of increased resolution outlined earlier, including greater eastward penetration of inertial jets, sharper definition of oceanic fronts, and better simulation of meandering currents and the mesoscale eddy field. The identical twin interannual simulations help distinguish between deterministic and nondeterministic model responses to the atmospheric forcing and are also valuable in model-data comparison studies and dynamical studies of oceanic anomalies. So far these results have been used in publications (1) about the impact of model resolution on the global thermohaline circulation (Shriver and Hurlburt, 1998), (2) showing that El Niño-generated Kelvin waves can propagate at least as far as Petropovlovsk, Russia on the Kamchatka peninsula (Fig. 1) (Metzger et al., 1998) and (3) showing effects on Gulf Stream variability including (a) interannual vs climatological wind forcing for the model and (b) the impact of Atlantic model boundaries at 9°N and 51°N by comparison with global model results (Hurlburt and Hogan, 1998). In addition these model results have been used in a DoD HPC success story (Hurlburt et al., 1998) and in numerous presentations. Subsets of model output have been distributed to researchers outside NRL.

Results from the 1/32° Pacific model and the 1/64° Atlantic model are shown in figures 2 and 3. The Pacific model provides a striking example of oceanic fronts and inertial jets (narrow parallel ribbons of color) that can span a large ocean basin in a high resolution model (as found in observations). Work has also begun on assimilation of satellite altimeter data into a 1/16° version of the Pacific model. In comparison with linear solutions and coarser resolution nonlinear simulations (not shown), the 1/64° Atlantic model dramatically demonstrates the impact of such high resolution on (a) the Gulf Stream pathway (marked by narrow ribbons of color) between Cape Hatteras, North Carolina and the Grand Banks off Newfoundland and (b) the formation of a large nonlinear recirculation gyre on the south side of the Gulf Stream which substantially impacts the large scale shape of the subtropical gyre (within the area surrounded by the yellow band). Results from this model are discussed by Hurlburt and Hogan (1998) in a paper on the impact of increased resolution on Atlantic simulations, especially on the Gulf Stream system. Results from both FY98 DoD Challenge simulations have been used in presentations.

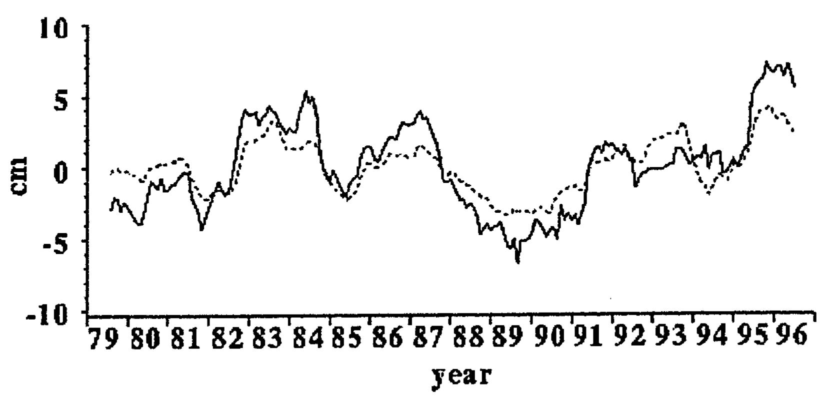

Figure 1. Sea level (in cm) vs time at Petropovlovsk, Russia (marked by a red dot at 53.1°N, 158.4°E on figure 2) from observed tide gauge data (solid line) and a 1/16° global ocean simulation (dashed line). The simulation was run as part of an FY97 DoD HPC Challenge project using the NRL Layered Ocean

Model (NLOM). The correlation coefficient between the two time series is 0.87. A 12-month running mean filter was applied to each time series to highlight interannual variability. This variability includes sea level rises due to the 1982-83, 1986-87 and 1991-92 El Niños via El Niño generated Kelvin waves which first traveled eastward along the equator, then counterclockwise around the rim of the North Pacific to this distant location. These Kelvin waves are clearly visible in animations of the model simulations. The unobserved sea level drop between 1993 and 1994 in the model time series coincides with the change from reanalysis to archived operational ECMWF wind forcing for the ocean model. The tide gauge data were obtained from the Integrated Global Ocean Services System.

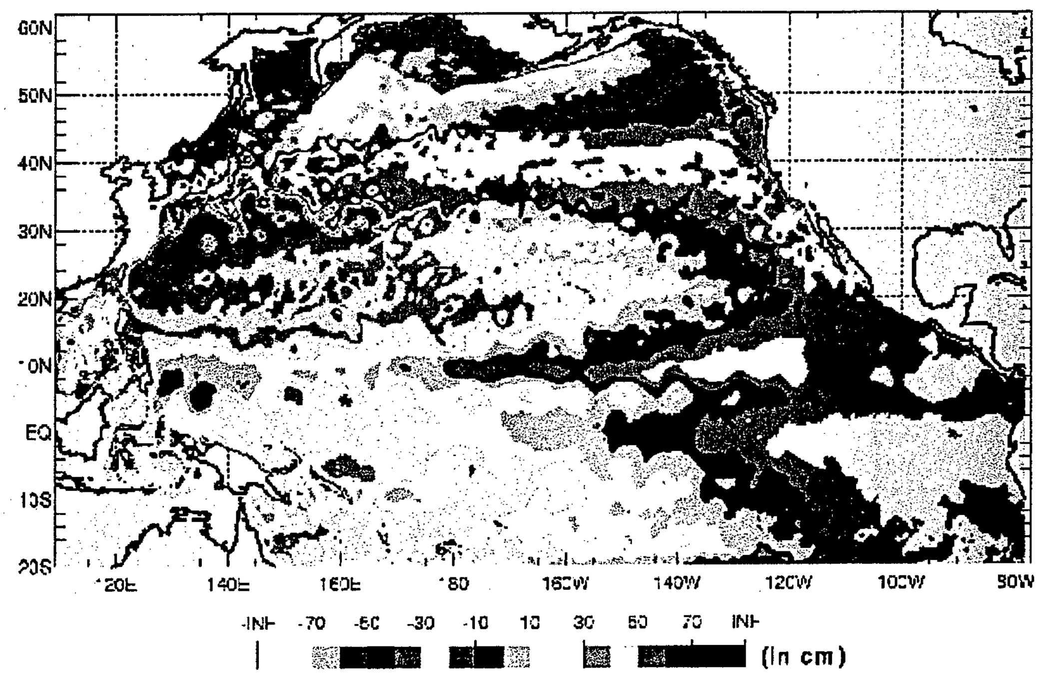

Figure 2. Sea surface height (SSH) snapshot from the 1/32° Pacific version of NLOM currently running as part of this FY98-00 DoD HPC Challenge project.

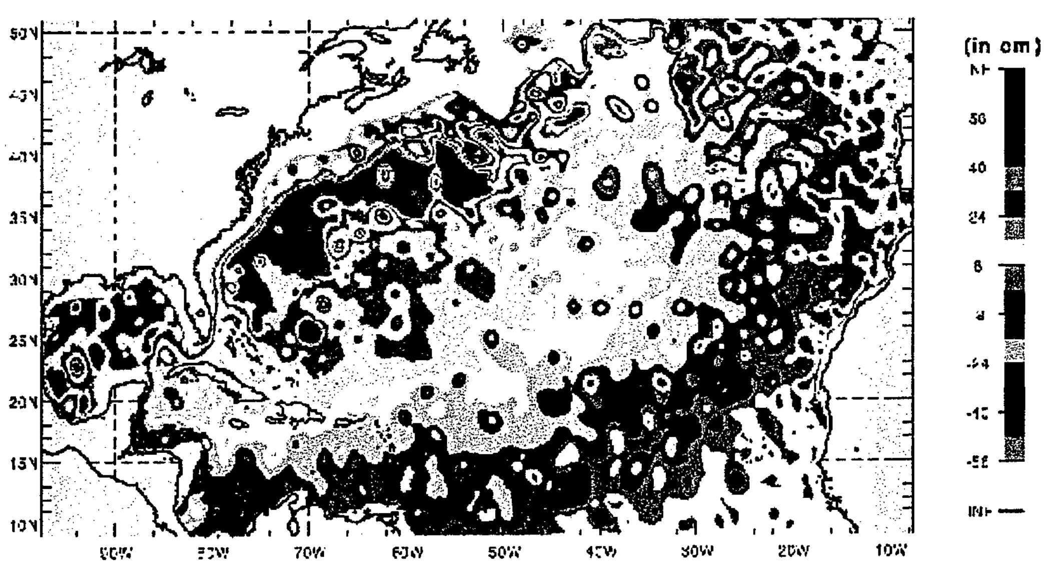

Figure 3. Sea surface height snapshot from the 1/64° Atlantic version of NLOM currently running as part of this FY98-00 DoD HPC Challenge project.

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